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QUADRUPOLE MIXED-SYMMETRY STATES IN ^{106}Pd **R. DE LEO¹, L. LAGAMBA***Dipartimento di Fisica dell'Università, I-70126 Bari, Italy
and Sezione dell'Istituto Nazionale di Fisica Nucleare, I-70126 Bari, Italy***N. BLASI, S. MICHELETTI, M. PIGNANELLI***Dipartimento di Fisica dell'Università, I-20133 Milan, Italy
and Sezione dell'Istituto Nazionale di Fisica Nucleare, I-20133 Milan, Italy***M. FUJIWARA, K. HOSONO, I. KATAYAMA, N. MATSUOKA, S. MORINOBU, T. NORO***Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567, Japan***S. MATSUKI***Institute for Chemical Research, Kyoto University, Kyoto, Japan***H. OKAMURA***Department of Physics, Kyoto University, Kyoto, Japan***J.M. SCHIPPERS, S.Y. VAN DER WERF***Kernfysisch Versneller Instituut, NL-9747 AA Groningen, The Netherlands*

and

M.N. HARAKEH*Natuurkundig Laboratorium, Vrije Universiteit, NL-1007 MC Amsterdam, The Netherlands*

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The isoscalar and isovector parts of the quadrupole transition matrix elements for the direct $0_{gs}^+ \rightarrow 2_1^+$ excitation of low-lying 2^+ states in ^{106}Pd are derived from the inelastic scattering of deuterons and of polarized protons. The isovector component for the 2^+ level at 3.070 MeV exceeds significantly the isoscalar one. This level is therefore identified as a mixed-symmetry state in the language of the neutron and proton interacting boson model (IBA-2).

New nuclear collective excitations at low energies corresponding to out-of-phase motion of neutrons and protons are predicted both by geometrical models [1,2] as T-vector (isovector) or "scissor states", and by the IBA-2 model [3,4], in which they are described as F-vector or "mixed-symmetry states". In

deformed even nuclei a systematical experimental search [5] for magnetic dipole $J^\pi = 1_M^+$ (M stands for mixed-symmetry states in the IBA-2 model notation [4]) scissor states has been performed over a wide nuclear mass interval using the inelastic scattering of electrons and gammas.

In non-deformed nuclei quadrupole ($J^\pi = 2_M^+$) mixed-symmetry states are predicted [4] to be the most intense in excitation strength and the lowest in excitation energy. Two experimental methods have

¹ Present address: Università degli Studi di Lecce, I-73100 Lecce, Italy.

been employed for the identification of these states, so far only on a limited number of nuclei. With the first [6–8] the mixed-symmetry states have been identified as those with an enhanced M1/E2 mixing ratio by looking at their γ -decay towards the 2_1^+ level. The results, which concern $N=84$ isotones, Sm isotopes, and ^{56}Fe , show that a strong part of the quadrupole mixed-symmetry strength resides on the third 2^+ level (2_3^+). With the second method [9] the ratio of the T(F)-vector or isovector (M_v) to the isoscalar quadrupole transition matrix elements (M_s) for the direct excitation of 2_1^+ levels is derived from the inelastic scattering cross sections of two probes with different isospin, namely protons and deuterons. An enhanced value of this ratio is taken as a signature of a mixed-symmetry state. The results of ref. [9] show a clear evidence for the existence of 2_M^+ states in $A \approx 110$ nuclei at energies between 2.5–2.9 MeV and, thus, well above the energy of the 2_3^+ level. This is in contrast with the finding of refs. [6–8], but, as stated below, is in agreement with the systematics of ref. [5] regarding the excitation energies of 1_M^+ dipole scissor states. No clear evidence for 2_M^+ states was found [9] in $A \approx 150$ nuclei.

In this communication we apply the method of ref. [9] to ^{106}Pd using a larger number of observables. This is achieved using a polarized proton beam. The proton experiment was carried out at the incident energy of 34.93 MeV and with an average polarization of 80% at the RCNP in Osaka. The unpolarized 51 MeV deuteron data were taken at the KVI in Groningen. A 98% enriched target with a thickness of the order of 1 mg/cm^2 was used in both experiments. An energy resolution of 15 and 20 keV, respectively for deuterons and protons, was achieved in the spectra which were obtained with magnetic spectrographs. Angular distributions were measured for all resolved levels up to 3.5 MeV excitation energy. Absolute differential cross sections were determined by normalizing elastic differential cross sections to the predictions of optical-model (OM) calculations. The uncertainties due to this normalization procedure are estimated to be less than 5%.

Spin assignments were obtained by comparing cross sections and asymmetries with coupled-channel (CC) calculations. These were performed using the following OM parameters (first and second values refer to protons and deuterons, respectively): $V=49.0, 89.2$

MeV; $r_2=1.165, 1.140$ fm; $a_R=0.781, 0.800$ fm; $W=4.15, 3.00$ MeV; $W_D=4.5, 11.6$ MeV; $r_w=1.276, 1.270$ fm; $a_w=0.712, 0.820$ fm; $V_{so}=6.0, 6.0$ MeV; $r_{so}=1.01, 1.01$ fm; $a_{so}=0.75, 0.70$ fm; $r_c=1.2, 1.3$ fm.

Ten levels were unambiguously identified as $J^\pi=2^+$ (see table 1), most of which are in agreement with levels reported in ref. [10]. In table 1, in fig. 1, and in the text, the lowest three of these levels are labeled by their order, whereas the higher seven ones are labeled by their excitation energies.

At the two incident energies which have been used here, the ratio of direct to two-step (through the 2_1^+ level) contributions for $L=2$ transitions, as evaluated by CC calculations, is approximately equal [9] in deuteron and proton cross sections. The availability of proton asymmetries has been found of considerable usefulness in identifying the magnitude of two-step effects and therefore in evaluating the direct strengths and in particular those to the 2_M^+ states.

Good fits were obtained for many 2_1^+ levels with only the $0_{gs}^+ \rightarrow 2_1^+$ direct coupling; other levels required two-step components through the 2_1^+ state. Some transitions required a second derivative form factor (ff). This ff is predicted by the IBA-2 model [11] in case of transitions conserving the number of d-bosons, and it has already been used earlier [12,13]. Only deformation parameters (and OM potentials) were allowed to be different in the fits to proton and deuteron data for a given transition. This procedure was found to work for all the detected 2^+ levels with the exception of the one at $E_x=3070$ keV. A good fit (solid curves in fig. 1) for the $0_{gs}^+ \rightarrow 2_{3070}^+$ transition was obtained only by allowing different ff's for the two probes. These were given by two different mixtures of first and second derivatives of Woods–Saxon potentials (∂' and ∂'' in table 1).

In ref. [10], a level observed in the (n, γ) reaction at $E_x=3069.9$ keV, has been classified as $J^\pi=(2^-, 3^-)$, whereas in ref. [14] levels with $J^\pi=2^+$ have been observed at $E_x=3055.2$ and 3083.2 keV. Although the determined excitation for the level we observe at 3070 keV and to which we assign a $J^\pi=2^+$ agrees well with that of the level assigned $J^\pi=(2^-, 3^-)$ in ref. [10], our data, compared with CC calculations, excluded both the 2^- and 3^- assignments. The 2^- assignment (calculations not shown) can be excluded on basis of both cross sections and asymmetry data. With a 3^- assignment (calculations

Table 1

Excitation energy, form factor, coupling scheme, deduced deformation parameters and quadrupole transition matrix elements for 2^+ states in ^{106}Pd . The deformation parameters and matrix elements have been obtained from fits with CC calculations including fits to proton asymmetries.

E_x (MeV)	Level	ff ^{a)}	Transition	$\beta_{p,p'}$	$M(E2)_{p,p'}$ ($e\text{ fm}^2$)	$\beta_{d,d'}$	$M(E2)_{p,p'}$ ($e\text{ fm}^2$)	$M_v(E2)$ ($e\text{ fm}^2$)	M_v/M_s
0.511	2_1^+	∂'	$0_{gs}^+ - 2_1^+$	-0.2307(56)	90.7(2.2)	-0.2265(5)	86.6(1.9)	-8.3(5.9)	-0.10(7)
1.128	2_2^+	∂'	$0_{gs}^+ - 2_2^+$	-0.0325(14)	12.8(6)	-0.0375(22)	14.3(8)	3.0(2.0)	0.21(14)
		∂'	$2_1^+ - 2_2^+$	-0.180(18)	70.8(7.1)	-0.183(13)	69.9(5.0)	-1.7(17.)	0.024(240)
1.560	2_3^+	∂'	$0_{gs}^+ - 2_3^+$	-0.0118(7)	4.6(3)	-0.0176(16)	6.7(6)	4.2(1.4)	0.63(22)
		∂''	$2_1^+ - 2_3^+$	0.0294(31)	19.5(2.0)	0.027(10)	17.2(6.3)	-4.6(13.)	-0.27(51)
1.910	2_{1910}^+	∂'	$0_{gs}^+ - 2_{1910}^+$	-0.0105(6)	4.1(2)	-0.0134(13)	5.1(5)	2.0(1.0)	0.39(20)
		∂'	$2_1^+ - 2_{1910}^+$	0.0812(55)	31.9(2.2)	0.074(15)	28.3(5.7)	-7.2(12.)	-0.25(43)
2.242	2_{2242}^+	∂'	$0_{gs}^+ - 2_{2242}^+$	-0.0111(7)	4.4(3)	-0.0093(8)	3.5(3)	-1.7(8)	-0.49(23)
2.823	2_{2823}^+	∂''	$0_{gs}^+ - 2_{2823}^+$	-0.0086(2)	5.7(1)	-0.0075(2)	4.8(1)	-1.8(3)	-0.38(6)
3.070	2_{3070}^+	∂'	$0_{gs}^+ - 2_{3070}^+$	-0.0084(8) \(\searrow\)	5.6(7)	-0.0041(4) \(\searrow\)	3.1(3)	-5.0(1.5)	-1.6(5)
		∂''	$0_{gs}^+ - 2_{3070}^+$	-0.0034(6) \(\nearrow\)		-0.0025(2) \(\nearrow\)			
3.250	2_{3250}^+	∂'	$0_{gs}^+ - 2_{3250}^+$	-0.0210(6)	8.3(3)	-0.0188(7)	7.2(3)	-2.2(8)	-0.31(11)
3.449	2_{3449}^+	∂'	$0_{gs}^+ - 2_{3449}^+$	-0.0136(10)	5.4(4)	-0.0116(6)	4.4(2)	-2.0(9)	-0.44(21)
3.490	2_{3490}^+	∂'	$0_{gs}^+ - 2_{3490}^+$	-0.0125(9)	4.9(4)	-0.0106(7)	4.1(2)	-1.7(9)	-0.41(22)
		∂'	$2_1^+ - 2_{3490}^+$	-0.103(7)	40.6(2.7)	-0.114(3)	43.5(1.1)	6.0(5.8)	-0.14(13)

^{a)} ∂' refers to first derivative ff and ∂'' to second derivative.

shown with dashed curves in the bottom part of fig. 1) a good fit could be obtained for only the (p, p') cross section data; the fit to the proton asymmetry data is of worse quality than that obtained with the $J^\pi = 2^+$ assignment (solid curves in fig. 1) and furthermore the fit to the (d, d') data, with parameters consistent with those of the proton channel, is of much worse quality than that with a $J^\pi = 2^+$ calculation. We therefore observe a different level than seen in the (n, γ) reaction or the assignment obtained from the (n, γ) reaction is incorrect.

Experimental differential cross sections and asymmetries, and the result of the CC calculations with the schemes of table 1, are shown in fig. 1 for the 2_{3070}^+ and the first three 2_i^+ levels, taken as examples. Different oscillation patterns are observed in the asymmetry, showing the presence of two-step contributions and different shapes of ff.

The transition matrix elements, $M(E2)_{p,p}$ and $M(E2)_{d,d}$, deduced from the deformation parameters of table 1 and from the quadrupole moments of the real part of the transition potentials are listed in columns 6 and 8 of the same table and shown in the upper part of fig. 2. The available experimental matrix elements [10] from electromagnetic studies are

also reported in fig. 2 with the label "e.m.". From these the T(F)-vector matrix elements M_v are immediately obtained as $M_v = 2(M_{dd'} - M_{pp'})$. They are reported in the ninth column of table 1 and in the middle part of fig. 2. The largest direct isovector strength is found in the 2_1^+ level; in the 2_3^+ and 2_{3070}^+ levels there is only about 60% of that, but the M_v/M_s ratio, reported in the last column of table 1, is significantly high only for the 2_{3070}^+ level. This state has therefore relatively the strongest component of mixed-symmetry 2_M^+ strength. The transitions leading to the 2_2^+ , 2_3^+ , 2_{1910}^+ and 2_{3490}^+ states are affected by large two-step contributions. The deformation parameters concerning the second step are determined in CC calculations with relatively large errors. The resulting M_v strengths are therefore determined with a poor accuracy. For none of these two-step processes the M_v/M_s 's in the last column of table 1 assume relevant values.

The same conclusion about the 2_M^+ strength can be drawn from the following considerations. In ref. [9] it was shown that proton and deuteron cross sections, at the above incident energies, have nearly the same shape, when plotted versus the transferred momentum, so that their ratio can be evaluated unambigu-

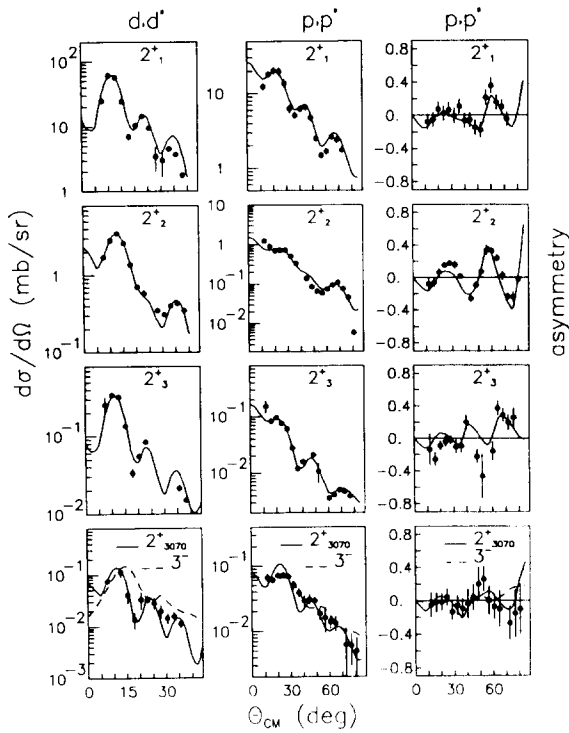


Fig. 1. Differential cross sections and asymmetries for protons and deuterons scattered from some 2^+ levels of ^{106}Pd . The solid curve show the results of CC calculations using the coupling schemes of table 1 and the OM parameters given in the text. Dashed curves are results of CC calculations with $J^\pi=3^-$ for the $E_x=3070$ keV level.

ously. Apart from possible effects caused by different contributions of two-step processes, a marked difference of this cross section ratio from the value for the 2_1^+ state indicates the presence of a predominant isovector component, and thus it characterizes 2_M^+ states. This latter ratio is reported in the lower part of fig. 2. It strongly differs from that of the 2_1^+ only for the 2_{3070}^+ level.

A fit of these strengths in IBA-2 with s-d bosons only permits to obtain values for neutron and proton quadrupole polarization charges (e_n , e_p) and the strength parameter of the Majorana force. In the IBA-2 hamiltonian this force is responsible for the shift in excitation energy between completely symmetric (with respect to the exchange of neutrons and protons) and mixed-symmetry states [15]. A set of parameters for an IBA-2 hamiltonian with s-d bosons

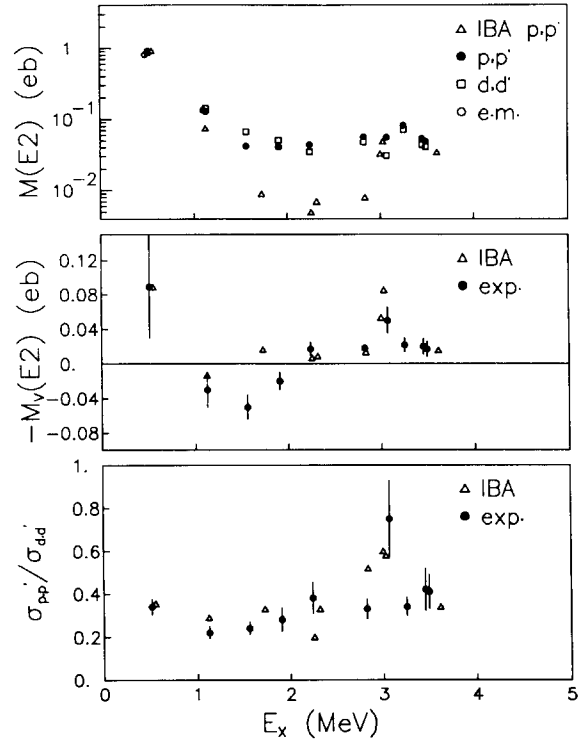


Fig. 2. Quadrupole matrix elements (upper part), and their isovector components (middle part) for the 2^+ states of ^{106}Pd . In the lower part the experimental ratios of proton and deuteron cross sections are plotted. The triangles show the results of the IBA-2 calculations described in the text. The open circles are results from electromagnetic studies [10].

only has been obtained in previous analyses [13,16,17] based on several Pd isotopes. Our best fit analysis of the matrix elements reported in fig. 2, and of the M_v trend in particular, started from this set of parameters ($\epsilon_d=0.90$ MeV, $k=-0.134$, $\chi_n=-0.9$, $\chi_p=0.2$, $cl_n=-0.428$, -0.361 , 0.0 , $cl_p=0.0$, 0.2 , 0.0 , $e_n/e_p=0.43$). Two parameters, (i) the structure and the strength of the Majorana force, and (ii) the ratio e_n/e_p of the quadrupole boson polarization charges, were left to vary because, given their particular sensitivity to isospin, they could not have been appropriately determined in the previous analyses.

Two structures have been suggested [15] for the Majorana force of the IBA-2 model:

$$M = \xi_2 (d_v^\dagger s_\pi^\dagger - s_v^\dagger d_\pi^\dagger)^{(2)} \cdot (\bar{d}_v s_\pi - s_v \bar{d}_\pi)^{(2)} - 2 \sum_{k=1,3} \xi_k (d_v^\dagger d_\pi^\dagger)^{(k)} \cdot (\bar{d}_v \bar{d}_\pi)^{(k)}. \quad (1)$$

The first [7] assumes $\xi_2=0$ and $\xi_1=\xi_3=-a/2$ and predicts the 2_M^+ strength to be mainly concentrated in the third or fourth 2_i^+ level. Varying the parameter a it is possible to move the excitation energy of these levels between 1.2 and 2 MeV but not to change the strength distribution. This structure of the Majorana force does not agree with the present results and with those of ref. [9]. The second structure [5,15] assumes equal values for the ξ parameters ($\xi_i=\lambda$) and also for the proton and neutron bosons structure parameters χ_π and χ_ν of the quadrupole operator (see e.g. ref. [5]). It is called the F-spin invariant structure since it predicts all the 2_M^+ strength in only one level and does not mix states with different F-spin number. An average value of $\lambda=0.18$ MeV has been found in ref. [9] for $^{104,110}\text{Pd}$ and ^{112}Cd . A link between the systematics of the excitation energy of $J^\pi=1_M^+$ states and the value of the ξ parameters divided by the quadrupole nuclear deformation β_2 is reported in ref. [5] for nuclei ranging from ^{46}Ti to ^{238}U . This link is given by the relation

$$\frac{\lambda}{\beta_2} = 4.3(N_\nu N_\pi)^{-1/2} \text{ MeV}, \quad (2)$$

where N_π and N_ν are the proton and neutron bosons numbers. This analysis also clearly shows that only this second structure of the Majorana force can reproduce the experimental peak of the dipole M1 strength distribution in rotational nuclei of the rare earth region around $A=164$. An expression similar to eq. (2) has been shown by Casten [18] to be valid for the excitation energies of 2_i^+ states. Abandoning the $\chi_\pi=\chi_\nu$ assumption, as done in refs. [16,17] for Pd isotopes, the isovector strength becomes fragmented over two or more levels even though, in agreement with the experimental evidence, the predominant part still resides in only one level. Increasing the value of λ the 2_M^+ strength can be moved to 2_i^+ states with increasing i -ordering numbers.

In the present analysis we adopted the second description of the Majorana force and we found $\lambda=0.22$ MeV and $\lambda/\beta_2 \approx 1$. As it happens for 1_M^+ scissor states, the structure and the strength of the Majorana force are linked to the excitation energies of 2_M^+ levels. The e_n/e_p ratio is instead linked both to the 2_M^+ strength, and to the isovector part of the strength of symmetric states. The ratio of polarization charges resulting from this analysis is $e_n/e_p=0.6$, in good agreement with the

value evaluated by Raman et al. [19] for the nuclei belonging to the ($28 < Z < 50$, $\approx 50 < N < 82$) shell. The fits to the matrix elements are shown in fig. 2 labeled "IBA". The calculated $M(E2)$ values underestimate the experimental strength between 1.5 and 2.8 MeV. This disagreement could be due to the fact that available IBA-2 codes do not allow the inclusion of other degrees of freedom, as g-boson or particle-hole excitations. With IBA-1 codes these degrees produce sizeable effects on weakly excited 2^+ states [20].

Summarizing we stress the point that the gross structure of the isovector strength of both symmetric and mixed-symmetry quadrupole states can be accounted for by the IBA-2 model. The obtained λ/β_2 value for ^{106}Pd is very near to the value of 1.36 predicted by eq. (2). Similar agreement can be obtained for other Pd isotopes from the values of ref. [9]. More systematics are, however, necessary to examine the possibility that this equation might be generally valid for 2_M^+ states in addition to 1_M^+ levels. The properties of 2_M^+ states in other mass regions of non-deformed nuclei is an information highly desirable for establishing systematic trends of non-well-known parameters, as the Majorana force and boson polarization charges.

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